DECO: a Design Space for Device Composition

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ABSTRACT

Numerous interaction devices are designed through device composition. However, there is no conceptual support for this process and designers are left out to explore the space of combinations in an ad-hoc manner. In this paper we propose a design space for device composition, DECO, which focuses on the physical aspects of the composition. This design space is built around two main axes, namely Physical arrangement, which describes how elements are physically combined, and Physical manipulation, which describes how users manipulate each element. We first classify existing devices using our design space and then compare four of them to illustrate their similarities and differences. Using DECO, we design a new compound device: RPM2. This device is based on the combination of a regular mouse with the Roly-Poly Mouse. We describe in detail the user-centered iterative design process that leads to the final prototype. Finally we propose a set of design guidelines to assist the use of DECO for device composition.

Author Keywords

Compound device; Design space; Device composition; Mouse.

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation: User Interfaces: Theory and methods

INTRODUCTION

In recent years, numerous research projects have designed and implemented novel interaction devices resulting from the combination or aggregation of existing ones [12, 19, 22, 25, 29, 37, 41]. Among them, we can cite a touchscreen on a mouse as in LensMouse [41], an air balloon inside a mouse as in Inflatable Mouse [22], two keyboards fixed together as in FlipKeyboard [12], or two tablets glued to form a dual-sided device as in Codex [19]. These projects followed an empirical design approach resulting in the development of ad-hoc solutions combining existing devices, without relying on a systematic or structured process. While these combinations proved to be useful in several contexts, designers who want to produce such type of devices are left out to explore multiple design alternatives on their own.

In this paper we investigate and refine the concept of **device composition** to promote the potential of combining existing devices to create new ones, and to leverage performing this combination in a more systematic manner. Device composition consists in **physically** putting together several existing devices to create a new one, hereafter referred to as a **compound device**. The concept of device composition can be related to the concepts of *multimodal interaction* and *composite device* [3, 16]. *Multimodal interaction* is based on the combination of several interaction modalities, each being defined as a couple of components: <device, language> [10]. In this paper we more specifically focus on the physical combination of two devices, instead of two modalities. The notion of *composite device*, as introduced by Bardram [3], defines the combination of interactive services and is thus far from the physical aspects considered in our approach.

In this work we develop the concept of device composition through the definition, illustration and evaluation of a design space for the physical combination of interaction devices. Our design space, **DECO**, is structured along two dimensions: 1) the physical arrangement, i.e. how the different devices are physically composed and 2) the physical manipulation, i.e. the way a user will manipulate each element of the compound device. Using DECO, we classify and compare existing devices to illustrate how our design space helps in describing and comparing different solutions.

In addition to the illustration of DECO on existing devices, we use this design space to elaborate a novel compound device supporting multi-dimensional interaction. This compound device aims at adding degrees of freedom to a traditional mouse. We describe in detail the user-centered iterative design process, using our design space, along four complete iterations involving user evaluations. These iterations prove that DECO contributes to the design of compound devices that are usable and perform well.

Our contributions are 1) the definition of the concept of device composition, 2) a design space, DECO, dedicated to device composition, 3) the classification and comparison of existing work using DECO, 4) the design and evaluation of a new compound device for multi-dimensional interaction and 5) an a set of design guidelines for applying DECO on device composition.

STATE OF THE ART

Our work is inspired by the large number of existing compound devices and by related work on composition toolkits and models for HCI. We synthesize these three sets of related works in this section and underline how DECO provides a novel perspective in terms of device composition.

Compound Devices

Device composition has largely been used in HCI. Such devices found in the literature can be classified into three main categories according to their interaction sense (input or output): 1) composition of two *input* devices to augment input interaction; 2) composition of two *output* devices to augment the output space; and 3) composition of *input* and *output* devices to provide an additional feedback on an input device (or vice versa). In this section we cite some examples without being exhaustive.

In the first category (*input-input*), a large body of work has been dedicated to the fusion of a mouse with another input device, most commonly with a tactile surface [2, 40]. A commercial example of this composition is the Apple's Magic Mouse. Some gamer's mice are based on a combination of a keyboard and a mouse [29]. Dedicated devices, such as the Lexip 3D [25] are based on the combination of a regular mouse with a joystick to offer additional degrees of freedom to support 3D manipulation tasks.

In the second category (*output-output*), most works are based on combining displays, such as Siftables, Codex, DualScreen or HoverPad [19, 23, 26, 32]. For instance, Siftables is based on the spatial combination of tiny screens [26]. Codex is a dual display mobile device [19]. Dualscreen combines two screens on a computer to share personal content to other users [23]. HoverPad is a compound device based on a self-actuated display on top of a tactile table [32].

Concerning the last category (input-output), one general approach is to add a display to an input device. For instance Yang et al. proposed LensMouse, based on adding a screen on the mouse [41] The opposite approach, i.e. adding input devices to a touchscreen, has been used in back-of-device prototypes [31, 36]. For instance, Sugimoto proposes to add a touchpad on the back of a PDA [36].

This general presentation of existing compound devices underlines their diversity and the multiplicity of composition alternatives. In the past, designers have explored this large composition space without any systematic or structured approach. In our work we propose a design space to support this exploration.

Composition toolkits in HCI

The idea of composition can be found in several HCI toolkits, from hardware platforms such as Arduino or Phidgets [35] to software IDEs such as OpenInterface or PureData [3, 9, 33].

Hardware toolkits help assembling and combining different sensors like pressure sensors, push buttons, light detectors, etc., resulting in a device based on sensor fusion. Phidgets [35] for example, propose multiple sensors that can be easily plugged together to create a device. Arduino [34] also proposes a set of actuators and sensors that can be combined to produce interactive devices. Hardware composition toolkits support the composition at a low level, i.e. at sensor granularity, but do not provide any help in guiding the design process or selecting design alternatives.

Other approaches developed the concept of composition at a software level. The OpenInterface platform [33] allows assembling abstract components and linking their input and output to develop a multimodal interaction. ContextToolkit [9] is another example using software components that encapsulate several types of sensors. It is then possible to combine those components to develop an interaction technique. Most of these software toolkits rely on analytical models to help identifying and structuring software components. However, they do not help determining how to design the physical combination of devices.

Rather than developing a concrete toolkit, the goal of the present work is to propose a theoretical framework. These existing software and hardware composition toolkits could actually be used to implement our theoretical approach.

Analytical approaches

In HCI, several works proposed to classify and describe input devices and their characteristics on the basis of the sensors used. Among them, Card's design space [8] defines three composition operators that can be used to combine sensors: Merger, Layout and Connection composition. Those three operators refer to the data composition (Merger), the spatial composition (Layout) and to the ability to plug the output of a sensor into the input of another sensor (Connection). Inspired by these three simple composition operators, our work is intended to propose a richer composition design space.

At a higher level of abstraction, multimodal properties were design to better describe the composition of interaction modalities. Allen [1] temporal properties define the temporal composition between two interaction modalities over time. The CARE [10] properties defines relationships between multiple modalities defined by a couple <*device, language*>. The fusion of modalities is performed at the language level. In our paper, we propose to refine these concepts by focusing on the composition of devices, not languages.

Closer to our approach, Hartmann et al. studied the combination of sensors with real devices [16] and enlightened the importance of the physical aspect. According to the authors, two devices or sensors that are designed to explicitly support their composition and that are aware of each other lead to a better resulting device. This type of composition is called "dovetail joint". Even if authors warn future designers against the risks of a bad composition, there is a lack of a design model that would better describe the properties of device composition.

To conclude, existing tools and properties describe the composition process at low level, using hardware or software toolkits, and at high level, using models to describe the composition of modalities. However we did not find any approaches focusing on the device composition process from a physical perspective. A design space to rationalize the composition process at a physical level would be a relevant complement to existing approaches, given the wide set of existing devices with different shapes, sizes or materials. To this end, we introduce DECO, a design space to inform the device composition process, using a set of relevant properties, in a similar way than other design methods such as annotated portfolio [7].

DEVICE COMPOSITION: DEFINITION

As seen in the previous section, existing work has paid little attention to identifying and analyzing the physical properties of device composition. Such consideration is crucial as it affects the interaction capabilities of the compound device. For instance, according to their relative position, two devices can be used simultaneously (e.g. a balloon and a mouse, as in Inflatable Mouse [22]) or only sequentially (a keyboard and a touchpad glued on its back, as in FlipKeyboard [12]). Altering the relative position of the components can also highly alter the resulting device: the LensMouse [41] would offer a completely different functionality if the touchscreen was placed on the side of the mouse instead of on its top.

Our concept of device composition takes this physical aspect into consideration. We define this concept as follows: a **device composition** is the physical assembly of several existing **elements**, according to a well-identified physical setting, and resulting in a **compound device**. The possible elements involved in a device composition include physical objects and devices.

This definition leads to two main design considerations:

- Physical arrangement: The integration of physical elements needs to consider their relative position and the alteration of their initial shape.
- Physical manipulation: Depending on the previous physical arrangement, different users' actions and body parts can be used to interact with the compound device. In addition, the device elements may be used sequentially or in a more interleaved manner, potentially allowing compound gestures.

These two design considerations are at the core of our design space, DECO.

DECO: A DESIGN SPACE FOR DEVICE COMPOSITION

The goal of DECO is to help designing new compound devices through **device composition** as previously defined. To achieve this goal, DECO is built around two axes: the *Physical arrangement* of elements (axis 1) and the *Physical manipulation* of the compound device (axis 2). We retain these two axes as they describe the two most important aspects of any device: its shape (**A1**) and its usage (**A2**).

Axis 1: Physical arrangement

The Physical arrangement axis (**A1**) depicts how the different elements are physically and/or spatially composed to create a compound device. These physical or spatial aspects have a direct impact on the device's final shape and on its physical manipulations, i.e. its usability and available DoFs. This axis describes the relative position of each element, how elements are physically linked together and how this arrangement varies over time. To address these considerations, we refine this axis into 3 properties: Topology, Fusion type and Dynamicity.

Topology. This property of DECO describes the spatial and physical organization of each element with respect to each other. We identified three possible categories for this axis: Enclosed, Glued and Separated (Figure 1).

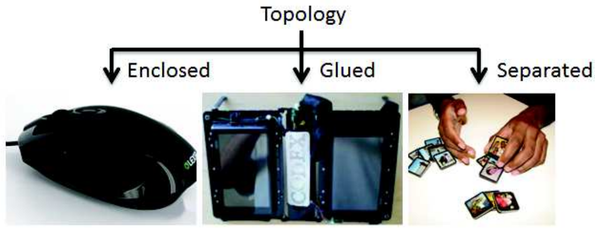

Figure 1: Illustration of the three *Topology* categories: *Enclosed* as in Lexip 3D [25], *Glued* as in Codex [19] and *Separated* as in Siftables [26].

Enclosed: The composition topology is *Enclosed* when one element is confined into another one. For instance, GlobeMouse [13] results from the insertion of a SpaceMouse into a 3DoF trackball. The Inflatable Mouse results from the insertion of a balloon into a mouse [22].

Glued: The composition topology is 'Glued' when elements are physically aggregated. This is the most common form of physical arrangement in compound devices. For instance, the LensMouse [41] is a compound device resulting from the assembly of a mouse and a touchscreen (elements are glued together, see Figure 2 - center). Codex [19] is a device created by fastening two tactile screens together (Figure 1 - center).

Separated: The composition topology is *separated* when multiple elements are spatially composed, i.e. their spatial relationship is detected. The pair of device (mouse, keyboard) for instance can not be considered as a compound device because they are not spatially composed. One example of *separated* compound device is Siftables [26]: these small displays are not *glued* together but can sense their relative position and orientation (Figure 1 - right). A particular instance of a *separated* topology is when the device is made of two separate elements not spatially related, but that can be *glued* if needed (see *dynamicity* later).

Fusion type. In the case of a *Glued* topology, a subsequent question is whether the physical shape of elements is altered to support the composition. Designers need to anticipate whether existing devices can be used or new ones must specifically be crafted. The Fusion type property describes which elements (if any) are altered during a composition. We identified three categories of *Fusion*:

(A-B) depicts the situation where elements are unchanged during composition: all elements are glued together without altering their original shape. For instance, a computer screen can simply be fixed to another one without further physical alteration as in the double-screen laptop Billboard [23] (Figure 2 - left). A similar approach is used in the FlipKeyboard [12], which is composed of a touchpad glued on the back of a keyboard.

(A←B) depicts the situation where the physical shape of element A has been modified (drilled, removed, reshaped, etc.) to accommodate or glue the element B. For instance in the case of the LensMouse [41] (Figure 2 - center), the mouse serves as a receptacle for a tactile screen: to place the touchscreen at an appropriate angle, the mouse cover has been altered and mouse buttons were also removed. In the Trackball Keyboard [37], a keyboard was carved to integrate a trackball on its top (Figure 4 - left).

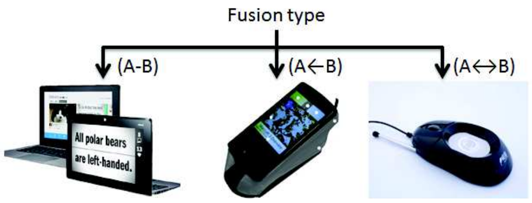

Figure 2: Illustration of the three *Fusion types*: *(A-B)* as in Billboard [23], *(A←B)* as in LensMouse [41] and *(A↔B)* as in Ink222 [20].

(A↔B) depicts the situation where the shape of both elements has been altered to support their composition. The Ink222 [20] mouse (Figure 2 **-** right) is a compound device based on a classical mouse and a touch tablet. In this case, the mouse was carved and the touch tablet was reshaped to fit a circular space. In the CapMouse [40] (Figure 6 - right), the mouse buttons have been removed and a touchpad has been adapted on top of the mouse.

Dynamicity. This property of DECO characterizes whether the Physical arrangement of a compound device changes over time. The physical arrangement is either *static*, i.e. defined once for all, or *dynamic*, i.e. it may change depending on the task, the user or the context (Figure 3). Usually, this property applies to the topology values *glued* and *separated*, when a device can shift from one to the other. For instance, Rooke M. [30] proposes multiple spatial arrangements between hexagonal bezel-less screens. Using *separated* screens, a user can perform selections and rotations whereas, using *glued* screens, a user can perform swipes or tilts (Figure 3).

Axis 2: Physical manipulation

The Physical manipulation axis of DECO describes how users manipulate the compound device's elements and aims to characterize its usage. From a physical perspective, focusing on the device usage means focusing on the device handling and on its expected manipulations. The Physical manipulation axis is thus described by 3 properties: Human effectors, Physical actions and Temporal usage.

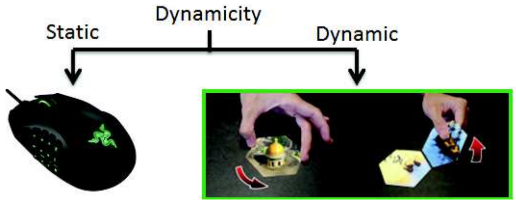

Figure 3: Illustration of the *Dynamicity* property: *static* as in the Razer Naga [29] and *dynamic* as the Hexagonal bezel-less screens [30].

Human effectors. This property of DECO identifies the body parts acting on each element of the compound device. Anatomical dependencies between human effectors may largely influence their use in a compound device [24]. A human effector may be for example one finger, one hand, one foot, or the combination of several of them. This property is described by the body part(s) involved in the interaction with each element. For example, the Trackball Keyboard [37] is a compound device designed for a bimanual use, with one hand on each element: it can be described by the couple <*keyboard: non dom. hand; trackball: dom. hand*> (Figure 4 - left). The Inflatable Mouse [22] is designed to be used with the dominant hand: it can be described by the couple <*mouse: dom. hand; balloon: dom. hand*> (Figure 4 - right).

This axis allows identifying whether several elements of the compound device involve the same body part, as with the Inflatable Mouse. In this case, the physical actions applied to each element need to be compatible, which may imply to adapt or modify one of the elements.

Figure 4: Illustration of the *Human effectors* property. Trackball keyboard [37]: *<keyboard: non dom. hand; trackball: dom. hand> (left)*. The Inflatable Mouse [22]: *<mouse: dom. hand; balloon: dom. hand> (right)*.

Physical actions. This property of DECO describes the expected user's physical actions on each element. Examples of actions include translations, rotations, swipe, etc. Existing notation such as UAN [17] may also be used to describe more complex actions. The role of this property is therefore to help anticipate the ability of the user to produce the expected physical actions on each element, anticipate conflicts and consider different design alternatives.

This property is further refined by the **degrees of freedoms (DoF)** involved by each physical action. The CubicMouse [14], for example, is a compound device combining a cube and three rods (Figure 6). The cube has a 6DoF tracking sensor that allows logging the device's position and orientation. It can be described as follow: *<Cube: translations (3DoFs), rotations (3DoFs); StickX: translation (1DoF); StickY: translation (1DoF); StickZ: translation (1DoF)>*.

Temporal usage. This property of DECO describes how the physical actions are expected to be performed over time. The temporal usage of an interactive system has already been described in the literature. Allen properties [1] describe the temporal composition of modalities. Simplified later with two operators in the CASE model [27]: *Parallel* and *Sequential*.

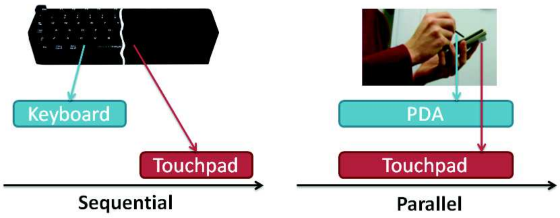

Figure 5: Illustration of the *temporal usage* property: sequential as in FlipKeyboard (left) and *parallel* as in HybridTouch (right).

In our design space we use these operators to define the temporal usage of elements in a compound device. Obviously, this property is influenced by the Physical arrangement and the Physical actions, which can prevent [20] or encourage [40] the concurrent usage of elements. For instance, the FlipKeyboard's [12] and HybridTouch [36] have the same Physical arrangement (*glued* on the back). However, in the FlipKeyboard, only one of its elements can be used at a time: the temporal usage is *sequential*. HybridTouch [36], based on the composition of a PDA and a touchpad, facilitates the concurrent usage of its two elements with a bi-manual interaction: the temporal usage is *parallel* (Figure 5).

CLASSIFICATION OF COMPOUND DEVICES

In this section we illustrate the use of DECO to describe a set of existing compound devices. We first give an overview of how these devices fit our space. Then we describe and compare in detail four existing devices to illustrate how our design space unveils their differences.

		Physical arrangement				
	Topology	Enclosed	Glued			Separated
	Fusion type		A-B	A<-B	A<->B	
Temporal usage	Sequential	GlobeMouse	Hexagonal bezel-less ★ FlipKeyboard Codex	Trackball Keyboard LensMouse	Ink222	Hexagonal bezel-less ★
	Parallel	Lexip 3D Inflatable Mouse	Razer naga Dualscreen HybridTouch	PadMouse CubicMouse RPM2 ★	Mouse 2.0	Siftable HoverPad RPM2 ★
★ = *Dynamic* compound device						

Table 1. Compound devices from the literature in DECO.

Physical and temporal classification

Among the properties identified for the two axes of DECO, we adopted a graphical representation based on the physical topology, the fusion type, the dynamicity and the temporal usage. The two remaining properties (human effectors and physical actions) correspond to n-uplets that are less appropriate for a graphical representation. In the table above, compound devices from the literature are positioned with regard to these selected properties of DECO. A star is used to highlight *dynamic* compound devices (Table 1).

This graphical representation highlights the diversity of existing compound devices. It also reveals that the design space is relevant to classify existing work as each possible combination of properties (cell) is illustrated with an existing compound device.

Comparison of compound devices with DECO

To illustrate DECO more precisely, we selected four compound devices from the literature: the CubicMouse [14], the GlobeMouse [13], the PadMouse [2] and the CapMouse [40] (Figure 6). While these devices seem similar in certain aspects, DECO allows comparing them and exposing their similarities and differences (Table 2).

Figure 6: From left to right, the Cubic Mouse [14], the GlobeMouse [13], the PadMouse [2] and the CapMouse [40].

GlobeMouse. This compound device is based on the composition of a SpaceMouse and a trackball. The SpaceMouse is *enclosed* in the trackball shell. The physical arrangement of this compound device is *static*. Only one hand of the user is required to manipulate the compound device: *<SpaceMouse: dom. hand; trackball: dom. hand >*. The expected physical actions can be formalized as follow: *<SpaceMouse: translation (3DoFs); Trackball: rotation (3DoFs)>*. These actions can only be performed *sequentially*.

CubicMouse. This compound device is based on four main elements: a physical cube localized in 6D (position and orientation in a 3D space) and three rods passing through the cube center. The cube and the rods are *glued* together. The cube has been altered to allow the positioning of the rods (Fusion type*: A←B*). The physical arrangement of the CubicMouse is *static*. The two hands of the user are required to manipulate the compound device: one for holding the cube and the other to adjust the rods <*cube: non dom. hand; rods: dom. hand*>. As discussed in the previous section, physical actions can be described as follow: <*Cube: translations (3DoFs), rotations (3DoFs); StickX: translation (1DoF); StickY: translation (1DoF); StickZ: translation (1DoF)*>. Physical actions on the rods and on the cube can be performed in *parallel*.

We use DECO to compare CubicMouse and GlobeMouse. The Physical arrangement of those devices differs, as their respective topology is *Enclosed* and *Glued*. The Physical manipulation differs too: the CubicMouse is a bimanual device, which offers a total of 9 DoFs, whereas the GlobeMouse can be used with one hand and offers 6 DoFs. Moreover, the CubicMouse provides a *parallel* usage and the GlobeMouse a *sequential* one. Our design space accurately highlights the differences between these two compound devices that differ both in terms of *physical arrangement* and *physical manipulation*.

PadMouse. This compound device is based on the composition of two elements: a regular mouse and a touchpad. The two elements are *glued* together. Only the mouse has been modified to produce the PadMouse: the mouse buttons have been removed to allow the composition with the touchpad (Fusion type*: A←B*). A digital button on the touchpad replaces the mouse buttons. The physical arrangement of PadMouse is *static*. To be physically manipulated the compound device requires only one hand. It can be described as <*mouse: non dom. hand; touchpad: non dom. hand*>. Physical actions include 2D translations of the compound device and 2D touch on the touchpad, represented as follow: <*Mouse: translation (2DoFs); Touchpad: touch input (2DoFs)*>. Finally, it is possible to use the elements in *parallel.*

In light of DECO, the CubicMouse and the PadMouse are similar in terms of Physical arrangement (*glued*, fusion type *A←B*, and *static*), but they strongly differ in terms of Physical manipulation. First, regarding the human effectors, the CubicMouse requires two hands whereas the PadMouse requires only one. In addition, the device composition has different effects in terms of DoF available: the buttons of the PadMouse were removed and their DoF replaced by the touchpad; in the CubicMouse, the DoF of each element were preserved. The comparison between these two devices highlights the ability of DECO to differentiate devices from the point of view of their physical manipulation, even if the physical arrangement is similar. This underlines the relevance of considering the physical manipulation as an axis of our design space.

CapMouse. This compound device is based on the composition of two elements: a regular mouse and a capacitive surface. These two elements are *glued* together but in this case, both elements have been modified to create the CapMouse (*Fusion Type A↔B*): the mouse buttons have been altered and the capacitive surface has been curved to fit the mouse shape. The physical arrangement of CapMouse is *static*. Under the capacitive surface, a single mouse button allows for mouse clicks. The *human effectors*, *physical actions* and *temporal usage* of this compound device are the same as in the PadMouse.

Although the CapMouse and PadMouse Physical manipulation are the same, their Physical arrangement highlights a fundamental difference. The CapMouse required physical modifications of both elements (fusion type *A↔B)*, whereas the PadMouse only of one of its elements (fusion type *A←B)*. As a consequence, designers could easily prototype new versions of the PadMouse by replacing the touchpad with another rectangular tactile device, such as a smartphone or a smartwatch for example. In other words, in the *A←B* fusion, designers can simply consider device variations based on the replacement of B, while in the *A↔B* fusion it would be more difficult as each element has been physically altered.

Summary: These four compound device descriptions and the most relevant comparisons using DECO enlighten the capabilities of our design space to accurately describe and distinguish existing solutions in terms of Physical arrangement and/or Physical manipulation (Table 2).

			GlobeMouse	CubicMouse	PadMouse	CapMouse
Physical arrangement	Topology	Enclosed	x			
		Glued		x	x	x
		Separated				
	Fusion type	A-B		x		
		A<-B			x	
		A<->B				x
	Dynamicity	Static	x	x	x	x
		Dynamic				
Physical manipulation	Human effectors	Dom. Hand	x	x	x	x
		Non Dom. Hand		x		
	Physical actions	Rotation	3 DoFs	3 DoFs		
		Translation	3 DoFs	6 DoFs	2 DoFs	2 DoFs
		Touch input			2 DoFs	2 DoFs
	Temporal usage	Sequential	x			
		Parallel		x	x	x

Table 2: Description of GlobeMouse, CubicMouse, PadMouse and CapMouse using DECO.

APPLICATION: RPM2

To assess the utility of DECO to generate new solutions, we report about the design and evaluation of a new compound device, RPM2, based on the combination of a regular mouse with a Roly-Poly Mouse (RPM) [28]. The RPM is a device, inspired by the roly-poly toy, with a circular basis that affords up to 5 DoF (2D translation and 3D roll and rotation).

Initial motivation

In this section, we detail the two main motivations that drove our design of a novel compound device combining the RPM and a mouse, namely the need to 1) overcome a technical challenge and 2) facilitate the adoption of RPM by making it compatible with the most widespread input device, the mouse.

The initial RPM prototype relies on an expensive infrared tracking system to log the position and orientation of the device. An embedded solution using a small 6 DoF sensor was proposed but lacks the precision of a laser mouse to track its 2D position. One solution to overcome this technical limitation is to combine the RPM with a mouse to benefit from its optical sensor. This solution has the additional advantage of drastically decreasing the cost of the resulting device.

To facilitate the adoption of RPM, we decided to envisage its usage as an extension of a classical mouse: RPM could then be used in conjunction with a mouse but also independently. From a DECO perspective, we wanted to propose a *dynamic* Physical arrangement: a device in which elements can be *glued* or *separated* depending on the usage context. For instance, when *glued,* the user can manipulate both elements with the dominant hand, while using the keyboard with his other hand. When the keyboard is no longer required, both devices could be *separated* and used in a bimanual mode, benefiting from higher precision with RPM.

Therefore, we decided to use DECO to guide our design process of a novel compound device combining the mouse and RPM. In the next section we illustrate the different versions of the new RPM (simply called RPM2) through an iterative user-centered design process using DECO. Participants involved in informal tests, pre-studies or evaluations (10 males and 2 females) were aged 24.8 on average (SD=3.6). All of them were right handed.

First iteration

We started by designing the *glued* version of the compound device: this version could potentially lead to physically altering one of the two devices (RPM or mouse) and therefore needed to be considered before exploring the *Separated* version. Our first step was to find the fusion type. We wanted to prototype a simple version of the device and improve it using DECO's second axis, the Physical manipulation. We built a cardboard prototype by using the fusion type *A-B* (no device is physically altered), since it is the simplest form of fusion.

The gluing mechanism relies on the use of an intermediate cardboard support. We made several prototypes by composing a USB mouse with a cardboard support on top of which RPM was placed, not altering any of the elements in the fusion process. We then varied the position of the mouse relative to the cardboard to test different physical compositions. This process led us to 5 different versions of the compound device according to the mouse position: on the left, on the right, on the front, on the back or under RPM (Figure 7). RPM was placed on the cardboard container but not attached to it to ensure free rotation of the device.

Figure 7: Cardboard prototypes of RPM2: the mouse is on the right side (left), on the back (center) or under (right) RPM.

We conducted a pre-study to evaluate the impact of the spatial *topology* of elements on usability and on the physical manipulations. We asked four users to manipulate all cardboard versions of RPM2. Users had to manipulate the compound device by performing translations, rotations, rolls and compound gestures (translation + roll). At the end of the experiment, users evaluated the device usability through an informal interview.

We found that the distance between the palm of the hand and the mouse, resulting from the cardboard support, had an impact on the usability of the device. This is due to the fact that, when RPM2 is translated, the cardboard slowly derives around RPM and the mouse is no longer aligned with the hand movement.

In addition, users declared that compound gestures were complex to perform on RPM2. This was also due to the distance between the two elements. As we wanted to keep the original RPM interaction properties, this was a main issue.

Second iteration: changing the fusion type

To solve the problems of the first prototype, we needed to allow the user to hold both the mouse and the RPM at the same time, i.e. reduce the physical distance between them. Using DECO, we searched for another fusion type that would get the two elements closer without altering the physical actions. In our context, a physical modification on RPM was impossible as it would impact the 3D rotation DoFs of the device. The fusion type *(A↔B)* was thus not appropriate. Therefore we decided to design a *(A←B)* fusion by considering how the mouse could be physically altered to incorporate RPM. One additional constraint was that both elements had to be *glued* without permanently fixing them to preserve the *dynamic* property of the device.

RPM2: Prototype v2

The second version of the compound device was overall smaller than the previous one as we removed the cardboard container. The cover of the mouse was replaced by a 3D printed version (Figure 8 - left). This cover was carved to hold RPM on it. A side effect was that we had to relocate the buttons on the side of the mouse. In parallel, we wanted to determine the optimal size of RPM as size could have an important impact on the physical manipulation of the device and on the user's comfort. To answer those design questions, we conducted a series of user tests.

In the first test, we varied the size of RPM to measure its impact on the *Physical actions*. Twelve users had to perform translations, rotations, rolls and compound gestures with the device. At the end of the experiment, participants were asked to evaluate the RPM size compared to the mouse size and they had to evaluate the device usability. The radiuses of the different RPM versions were 4, 5, 6, 8 and 10cm.

According to results, the optimal size for RPM was 5cm. With this size, both elements had almost the same width and allowed for a more comfortable hand posture. Moreover, users preferred to place the buttons on the left side of the mouse rather than on the right (Figure 8 - left) because pressing the buttons with the thumb (on the left) is less tiring than with the ring or little fingers (on the right). This confirms the importance of properly choosing the *human effectors* for each element.

To assess the device efficiency in a concrete task, we conducted a second test where we asked users to perform a 2D pointing task following the Fitts law [35] experiment protocol. Four users had to select among 25 circularly arranged targets using our device and a regular mouse. We evaluated six index of difficulty (defined as a ratio of the target size on the support circle size): 3.17, 3.70, 4.08, 5.93 and 6.33. Results showed that pointing with the mouse was faster than with RPM2. Pointing errors, i.e. missing the target, were significantly higher with our prototype. Participants' feedback revealed that the printed 3D support was hard to grasp: "The support is not steady, it's complicated to hold it correctly while I click." or "The support shape is not well suited. It was uncomfortable to grasp.".

RPM2: Prototype v3

Based on these results, we built a third version of the compound device. We removed the 3D printed support and directly carved the cover of a mouse to hold the 5cm RPM. With the best size for RPM defined, we explored the buttons location through another user test. The task was to perform translations, rotations, rolls and compound gestures with RPM2. Users had to manipulate two versions of the compound device: one on which the mouse was carved on the center and the buttons were placed on the left side (prototype v3a, Figure 8 – center); and one on which the mouse was carved on the right, leaving the original left mouse-button available (prototype v3b, Figure 8 –right). These two solutions required the use of different human effectors to press the button (thumb or index) but also to manipulate (rotate or roll) RPM.

The first result of this test is that users preferred the version with RPM on the center (prototype v3a). This is due to the fact that, when RPM is displaced on the right, the hand posture is particularly uncomfortable when performing rotations and rolls: the index finger lays on the left click while all the other fingers lay on RPM. Not only RPM manipulation is more complicated but also the posture is rather tiring. In addition, users found that compound gestures were easy to perform on the version carved on the center. In this version, the physical manipulation of RPM is performed using the three middle fingers.

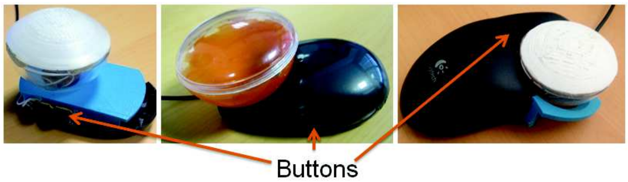

Figure 8: Different versions of the (A←B) compound device, from left to right: based on a 3D printed support (prototype v2), carved on the center of the mouse (prototype v3a) and carved on the right side of the mouse (prototype v3b)

Based on these results, we re-evaluated the compound device with four users in a 2D pointing task following the same protocol than before. Results showed a significant improvement in the compound device performance (10% better than the previous version). However, the prototype v3 still had a lower performance and a higher error rate than the regular mouse. Participants' feedback showed that this performance loss was due to a hard resistance of buttons, difficult and tiring to push with the thumb during a long period of time. Consequently, we improved the prototype by integrating softer buttons (Figure 9 – left).

Third iteration: Designing parallel temporal usage

After focusing on the Physical arrangement of the compound device, we focused on the temporal usage of its Physical manipulations. Our goal was to support compound gestures, i.e. *parallel* temporal usage of the device elements. While we included compound gestures in our previous iterations, we did not specifically focus on these gestures.

To evaluate the parallel usage of RPM2, we designed an experiment based on a multi-dimensional graphical task: rotate, scale and translate (RST, Figure 9 - center) [38]. Four users had to manipulate virtual rectangles in a 2D environment and dock them on a target rectangle. To move the rectangle, users first pressed the left click and then translated the device. To rotate and scale the rectangle, users could respectively rotate (left-right rotation) or roll (front-back rotations) the RPM. All three RST tasks could be performed in parallel with the RPM2 prototype v3a. At the end of the experiment users were asked to evaluate the device usability. We compared our device against the regular mouse, used as in PowerPoint (e.g. with anchors around the rectangle).

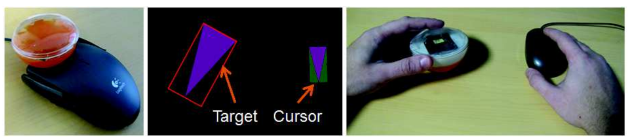

Figure 9: The *glued* RPM2 prototype v3 (left), a random trial from the RST experiment (center) and the *separated* RPM2 compound device (right).

The results reveal that our device is only 9% slower than the regular mouse, which means that our device is promising but the mapping between gestures and tasks needs to be improved. We observed that most users performed rotate, scale and translation in *parallel*. Actually, users found that RPM2 was “a good device because the manipulations are intuitive” and that “RPM2 is faster because I can scale and translate the rectangle at the same time”.

These results clearly show that we succeeded in designing a novel compound device using our design space, DECO, as a designing tool. The prototype v3a is *glued* and the experiment results established the device usability and performance, close to a regular mouse. Our main goal being to propose a *dynamic* device, we carried a last iteration to validate its usage in a *separated* topology.

Fourth iteration: From a *Glued* to a *Separated* topology
In our compound device, RPM and the mouse are not physically fixed. Therefore to come up with the s*eparated* topology, we simply take each element with a different hand and uncouple them (Figure 9 - right). The mouse cover still has a hole that impedes using the device normally: a solution can be to use a mechanism to close the hole when RPM is removed. In this iteration, we did not build this solution and used a regular mouse without hole as we focused on the performance of the bimanual interaction.

The bimanual interaction technique is based on the use of a regular mouse with the dominant hand and the RPM with the other hand (*human effectors: <mouse: dom. hand; RPM: non dom. hand>*). This compound device still offers 5 DoFs and supports the following physical actions*: <mouse: translation (2DoFs), RPM: rotation (3DoFs)>*. The two elements can be used in *parallel* (temporal usage).

We evaluated the performance of this new version of RPM2 (RPM2-Separated) through a rotate, scale and translate (RST) experiment. We compared the bimanual technique with a regular mouse under the same conditions as in the previous iteration. Twelve subjects performed the experiment. Results revealed a significant difference between the two interaction techniques: the compound device performed faster than the mouse (22% faster). These results show that the *Separated* version of RPM2 performs better than its *glued* counterpart and illustrates the interest of developing a *dynamic* compound device: according to the task to perform, the user will be able to easily adopt the *glued* or the *separated* version of the compound device.

Summary
We proposed a novel *dynamic* compound device, the RPM2. It can be used as a *glued* compound device or as a bimanual *separated* compound device. A series of tests show that RPM2 is an efficient device in both Physical arrangements. To design these two versions of RPM2, we used DECO in a user-centered iterative design process: we guided our design process with the two axes of DECO and used its properties to iteratively propose several prototypes (Table 3).

		Physical arrangement				
	Topology	Enclosed	Glued			Separated
	Fusion type		A-B	A<-B	A<->B	
Temporal usage	Sequential		Iteration 1	Iteration 2		
	Parallel			Iteration 3 ★		Iteration 4 ★

★ = ***Dynamic* compound device**

Table 3. RPM2 design iterations in DECO.

To sum up, this illustrative example shows that DECO is a useful tool for designing novel compound devices.

DISCUSSION

DECO to describe, compare and generate solutions

In this paper we presented DECO, a design space for device composition. As illustrated on the RPM2 case study, using DECO, designers can explore the implications of a given design by changing some parameters among DECO's axes. DECO's axes also constitute leverages for suggesting new design possibilities, based on properties observed in different situations of device composition. As such, DECO contributes to research through design [15].

To validate our design space, we used the approach proposed by Beaudoin-Lafon [4] to evaluate design models. This approach is based on three properties characterizing the ability of a model to describe existing solutions (descriptive power), compare existing solutions (evaluative power), and generate novel solutions (generative power). The relevance of such a validation has already been established in previous work seeking to evaluate interaction design approaches [11, 21]. Concretely, to validate the descriptive power of DECO, i.e. its ability to describe a wide range of different solutions, we described and classified existing compound devices using the *Physical arrangement* axis and the *Temporal usage* property of our design space. To validate the evaluative power of DECO, i.e. its ability to differentiate multiple solutions, we compared four of these devices and illustrated how DECO helps identifying their similarities and differences in terms of physical arrangement and manipulation. Finally, to validate the generative power of DECO, i.e. its ability to create new design solutions, we generated a novel compound device based on the combination of the regular mouse with the Roly-Poly mouse [28]: we used DECO to explore several design alternatives in a user-centered iterative design process.

Through this 3-part exploration, we demonstrated that DECO is a useful design space that can be used to describe, compare and generate novel compound devices.

Guidelines for generating compound devices

Generating and designing new devices often rely on an empirical approach that combines creativity and practical knowledge, as described in [39]. However, the lack of inspiration may affect the ideation phase of the design process. In the particular context of device composition, DECO is a structured analytical approach that seeks to offer designers a leverage to stimulate idea generation and to produce design alternatives. Combining such a formal approach with more informal design resources such as a brainstorming is possible and has already been proposed in HCI [6].

To help designers take advantage of DECO in a design process, we propose a set of lessons learnt during our experience in designing RPM2 with DECO.

Physical arrangement: One of the first steps, when designing an interactive device, is to analyze the users' requirements, tasks and context of use. These aspects may particularly impact the possibilities in terms of physical arrangement of the elements. At this design stage, using DECO should lead to choosing a specific topology. The two possible choices are an *Enclosed/Glued* topology, which leads to a single physical object, or a *Separated* topology, which leads to several objects.

In the case of a *Glued* topology, the advantage of starting with the *(A-B) fusion* is that it does not induce any modification on the initial devices. This allows evaluating early prototypes and getting feedback before considering physical alterations on any of the elements involved in the device composition.

Physical manipulation: The design of the Physical manipulation attributes needs to be reconsidered after each design iteration on the Physical arrangement. Even small physical changes in the prototype can induce large differences in terms of manipulation: for example, in our experience with RPM2, changing the size of the RPM considerably impacted its usability.

Finally, when the goal is to produce a *parallel* usage of the device, a good approach is to start designing and evaluating a *sequential* usage in the first iterations: the idea is to validate that each element can be properly manipulated and identify their potential in terms of manipulation (maximum range, stability, accuracy, etc.), before considering the combined manipulation.

Limitations and future work

In this paper we presented a first design space for device composition. We identified some limitations in terms of generalizability, granularity and property definition that we detail below.

In our work we mainly considered compound devices made of only two elements. While the related work on devices combining more than two elements is limited, we still need to generalize the use of our design space and assess its ability at describing, evaluating or helping generate compound devices based on more than 2 elements.

The definition of DECO has been largely driven by a critical analysis of compound devices presented in the literature. These solutions clearly focus on the combination of existing devices such as a mouse and a touchpad, i.e. the combination of two sets of sensors and physical objects. While we adopted the same approach to define the concept of device composition, DECO might also constitute a good support to analyze combinations at a finer grain of detail, i.e. at a sensor level. Future work will look into extending our design space to consider fusion composition.

In the future, we also plan to further analyze and refine the characteristics of the *Separated* topology. This case is particularly interesting for multi-surface systems, i.e. composing different interactive surfaces. We can for instance explore the geometric and spatial relationships between surfaces. Describing the Physical manipulations in this case will also require an extension of DECO to describe interactions such as mid-air or around-device gestures [5], which also have spatial properties.

CONCLUSION

In this paper we introduced DECO, a design space for device composition focusing on its physical dimensions. DECO is structured along two axes: Physical arrangement and Physical manipulation. The Physical arrangement axis describes the topology of the composition (Enclosed, Glued or Separated), the fusion type (which device is physically modified to produce the composition) and the dynamicity of the physical arrangement. The Physical manipulation axis describes the human effectors, i.e. the body parts, used to manipulate the device, the physical actions and the temporal usage of the elements. We used DECO to classify existing compound devices and compare alternative existing solutions. To illustrate the generative power of DECO, we designed a novel compound device by combining a mouse with the Roly-Poly Mouse in a user-centered design process. Finally, we proposed a set of guidelines to help designers apply our design space to create novel compound devices.

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